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Application of a new methodology for coastal multi-hazard-assessment & management on the state of Karnataka, India

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A B S T R A C T

This paper presents the application of a new methodology for coastal multi-hazard assessment & management under a changing global climate on the state of Karnataka, India. The recently published methodology termed the Coastal Hazard Wheel (CHW) is designed for local, regional and national hazard screening in areas with limited data availability, and covers the hazards of ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding. The application makes use of published geophysical data and remote sensing information and is showcasing how the CHW framework can be applied at a scale relevant for regional planning purposes. It uses a GIS approach to develop regional and sub-regional hazard maps as well as to produce relevant hazard risk data, and includes a discussion of uncertainties, limitations and management perspectives. The hazard assessment shows that 61 percent of Karnataka's coastline has a high or very high inherent hazard of erosion, making erosion the most prevalent coastal hazard. The hazards of flooding and salt water intrusion are also relatively widespread as 39 percent of Karnataka's coastline has a high or very high inherent hazard for both of these hazard types.

1. Introduction

The projected climate change will place significant stress on coastal regions worldwide and constitutes a particular challenge for developing countries where coastal development often happens rapidly and without prior investigation of natural dynamics. Improving the knowledge of the physical characteristics of coastal areas as well as their inherent natural hazards is therefore an important prerequisite for sustainable and safe coastal development. This paper tests the practical application of the CHW framework (Rosendahl Appelquist, 2012) through a multi-hazard assessment of the coastline of Karnataka, India, under a changing global climate (IPCC, 2007). The goal of the paper is both to showcase a practical procedure for applying the CHW framework for regional hazard assessments, and to develop hazard maps and hazard risk data for the hazards of ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding for the state of Karnataka, India.

As the CHW framework was published in late 2012, the hazard assessment for Karnataka is intended to test its practical applicability on a diverse and largely sedimentary coastline. Whereas most existing assessment systems are designed for areas with relatively good data availability (Thieler et al., 2000; Ramieri et al., 2011), the CHW framework is developed to be used for hazard screening and assessment in areas with limited geophysical data collection systems. The state of Karnataka is therefore considered a good test case as coastal data for this region is relatively sparse but not completely absent.

The CHW framework is designed to be applied in a stepwise manner, depending on the appropriate scale and resolution of the hazard assessment. At Step 1, the framework can be applied for regional and national hazard screening, and in most cases, this can be carried out based on publicly available geophysical data and remote sensing information. For areas that are of particular interest or are indicated as hazard hotspots in the hazard screening, a more detailed assessment can be carried out as Step 2. In this step, it is recommended to supplement the data obtained in Step 1 with representative field verification. If local hazard information is needed, Step 3 can be carried out by supplementing data from step one and two with detailed local data collection. The user of the CHW framework can choose only to carry out the step relevant for

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their specific needs, but should be aware of the appropriate data requirements for each assessment step. The step-wise approach means that data collection can be adjusted according to the scale and resolution of the assessment and should therefore lead to an appropriate balance between data requirements and assessment detail. As this paper focuses on regional hazard screening, the assessment relies solely on published geophysical data and remote sensing information.

The regional hazard screening for Karnataka can be carried out based on relatively simple means and should therefore be replicable without major difficulties in other locations worldwide. The paper is written so it can function as a guided example for coastal planners and developers who are interested in producing hazard maps and hazard data using the CHW framework. The data used for the assessment is available at low/no cost from the internet or regional institutions and it is expected that the same will be the case for most other world regions. For the assessment, it was decided to acquire some supplementary RapidEye satellite images to cover a few low-resolution gaps in ESRI's ArcGIS image series from ArcGIS Online and this added some extra costs to the assessment. It is expected, however, that the quality of satellite images available in ArcGIS and Google Earth will continue to improve and supplementary satellite images should therefore not be necessary for most locations in the near future.

Since the CHW framework is based on geo-biophysical properties of natural coastal systems, it gives information on the inherent hazards of the different coastal environments. Where human activities have altered a coastal area, the inherent hazards for that generic coastal system are likely to be affected. The CHW framework is able to take most human alterations into account such as changes in sediment supply from river damming and changes in wave climate due to harbour construction. However, if the human activities alter a coastline to a level outside its natural occurrences such as by completely removing a mangrove forest in an otherwise natural mangrove area or constructing a large dike in a coastal plain, the framework is unable to take these changes into account. With the data sources used for this hazard screening, it can in many cases be quite difficult to capture smaller human alternations of the natural coastline, but as a Step 1 assessment, these alterations should not have a great impact on the general hazard profile of the coastline. For more detailed hazard assessments, however, human activities such as sand mining could have a significant impact at a local level and appropriate field verification is therefore recommended if Step 2 or 3 should be implemented.

2. The Coastal Hazard Wheel framework

The CHW framework is developed as a screening and assessment tool to assist coastal planners and decision-makers in determining the hazard profile of a particular coastal area under a changing global climate. This could be relevant for regional infrastructure planning, expansion of residential areas and protection of sensitive natural sites, as well as for determining hazard mitigation strategies for coastal stretches. The CHW framework is based on a specially designed coastal classification system that contains 113 generic coastal environments. The system incorporates the main geo-biophysical parameters determining the characteristics of coastal systems and aims to cover all coastal areas worldwide. It uses the coastal geological layout as a basis on which it adds the main dynamic parameters and processes acting in the coastal environment.

The framework provides information on the degree to which key climate-related hazards are inherent in a particular coastal environment, defined as the hazards being an integral part of the geo-biophysical properties of a coastal system when exposed to future climate change. The framework covers the inherent hazards of ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding, and a total of 565 generic hazard evaluations are included in the system, each graduated into four different hazard levels based on a scientific literature review. The framework is generally designed to be applied in locations with limited data availability and computing capacity.

The CHW framework is provided as a graphical tool – the Coastal Hazard Wheel – to facilitate its application for planning purposes. The user starts in the centre of the CHW and then moves outwards, ending with the inherent hazard evaluations in the outermost circles. Starting from the centre, the coastal classification parameters comes in the following order where each category is represented by a new circle: Geological layout, wave exposure, tidal range, flora/fauna, sediment balance and storm climate. The inherent hazards then come in the following order: Ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding. In the practical application of the assessment framework, the user should make a new assessment every time any of the classification parameters changes significantly. This can be done by visually assessing the coastal appearance either in the field or through remote sensing, combined with evaluating data for the individual dynamic parameters. When conducting the assessment, the user should be aware of human alterations of the natural environment and whether these alterations are of permanent character, as this would have an impact on the coastal classification and hazard levels. The CHW is shown in Fig. 1 and a detailed description of the assessment methodology, assumptions and limitations can be found in Rosendahl Appelquist (2012).

3. The coastline of Karnataka

The state of Karnataka is bordering the Arabian Sea and has a tropical monsoon climate. The months from March to May constitute the hot season with the hottest temperatures occurring in May. The state receives heavy rainfall between June and September due to the SW monsoon and the average annual rainfall is close to 4000 mm of which about 80 percent is received during the SW monsoon season (Dwarakish et al., 2009; Kumar et al., 2010). The heavy monsoon rainfall leads to increased river flows and sediment transport to the coastline (Jayappa et al., 2003). Winds are strong and mainly westerly or south-westerly during the SW monsoon months. In the remaining months, the wind generally blows from northern and eastern directions in the morning and from western and north-western directions in the evening (Jayappa et al., 2003). Deep-water waves approach the coast from south-western and north-western directions and the significant wave height, Hs, have been assessed to >3 m during the SW monsoon (Kumar et al., 2010). It has been observed that the long-shore currents are strongest and towards the south during the SW monsoon (Narayana et al., 2001).

The coastline of Karnataka can generally be divided into two main geomorphologic sections with somehow different characteristics. The northern part is composed of Precambrian crystalline gneiss, schist and granite rocks, fronted by a narrow coastal plain of alluvial or Tertiary deposits. In locations where the rock extends to the coastline, coastal cliffs and rocky shores are formed. The coastline displays characteristics of submergence with drowned river valleys, estuaries and many small inlets (Nayak and Hanamgond, 2010). The southern part of Karnataka has extensive straight beaches backed by estuaries with low estuarine islands and mangroves. Sand spits growing northwards often border the estuaries (Nayak and Hanamgond, 2010).

The northern part of Karnataka's coastlines has a relatively low level of industrial development with small fishing villages located along the coast. However, due to a growing tourist industry,

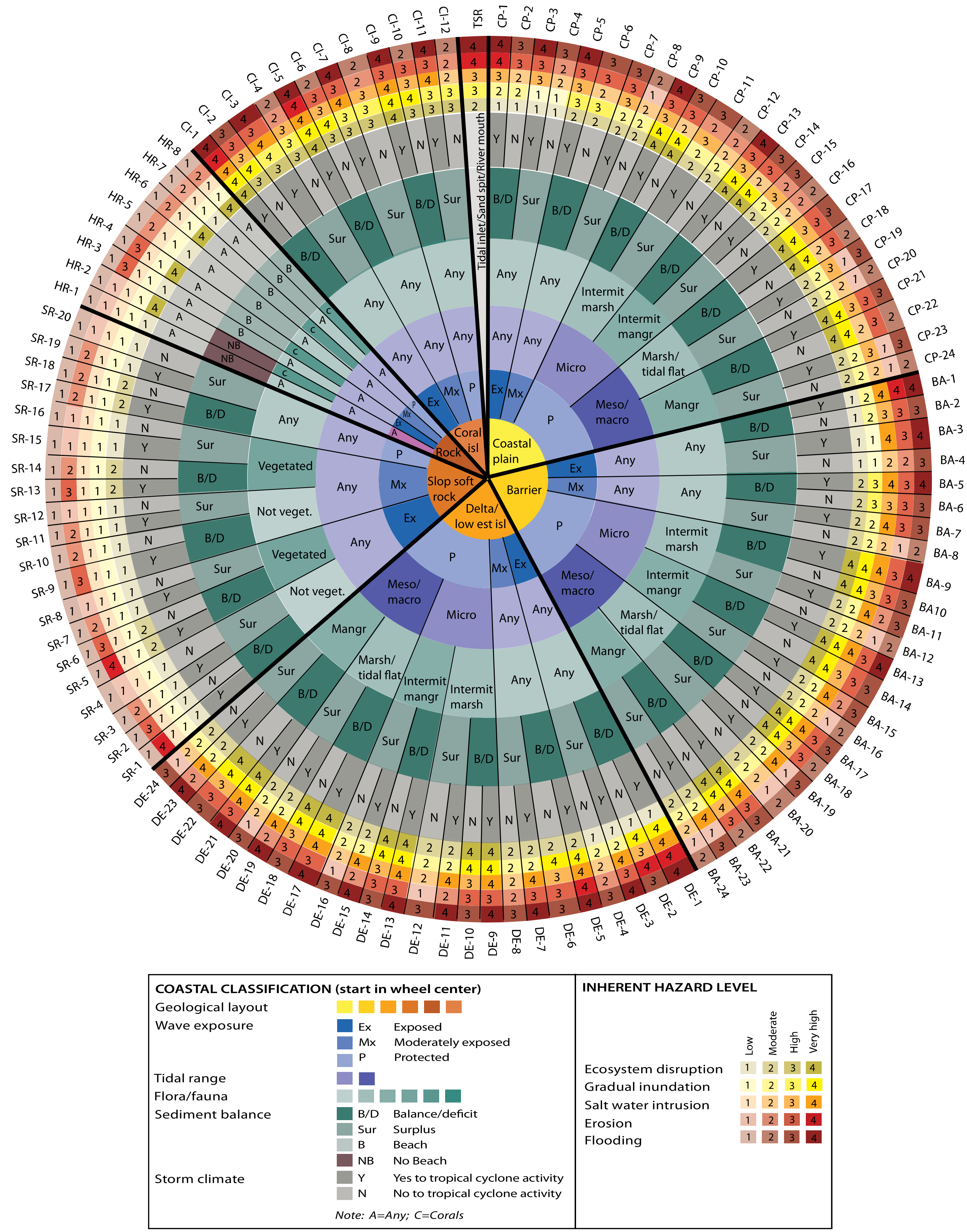

Fig. 1. The Coastal Hazard Wheel consisting of six geo-biophysical classification circles, five hazard circles and the coastal classification codes. In the classification code, CP stands for coastal plain, BA for barrier, DE for delta, SR for sloping soft rock, HR for sloping hard rock, CI for coral island and TSR for tidal inlet/sand spit/river mouth (Rosendahl Appelquist, 2012).

increased fishing intensity and industrial aquaculture, the coastal area is under growing pressure from human activities (Equations, 2000). The southern part of Karnataka's coastline close to the city of Mangalore has been used for heavy industrial development for several decades. The transformation from traditional fishing and farming activities started with the construction of the New Mangalore Port in the 1970s and today, many large-scale industries including chemical and petroleum processing plants are located along this coastline. The port of Mangalore is India's ninth largest harbour in terms of cargo handling and handles 75 percent of India's coffee export (World Port Source, 2012). The entire coastline of Karnataka has been declared special tourism area for promotion of tourism (Equations, 2000).

The coastline of Karnataka generally faces severe erosion during the SW monsoon and accretion during the fair weather season (Jayappa et al., 2003). In southern Karnataka, research indicates that most of the sand lost during the SW monsoon is regained during the calmer months (Jayappa et al., 2003). However, some parts of Karnataka's coastline show continuous and significant erosion (Dwarakish et al., 2009). In some locations, beach width has been reduced to zero due to reduction in sediment supply from human activities such as construction of breakwaters and seawalls and damming of rivers (Kumar and Jayappa, 2009).

Hard engineering structures including breakwaters, seawalls and revetments have been constructed along Karnataka's coastline over the past decades with varying success. Soft measures such as beach nourishment have generally not been applied due to economic reasons (Jayappa et al., 2003) although nourishment has been carried out at Thannirbhavi in January 2000 (Kumar and Jayappa, 2009). Legal and illegal dredging and sand mining from beaches, estuaries and upstream rivers has resulted in sediment deficits in some locations (Jayappa et al., 2003) and a recent increase in sand mining has lead to accelerated erosion (Kumar and Jayappa, 2009).

4. Data for the hazard assessment

The hazard assessment makes use of data that is available in the original CHW framework paper or that can be easily obtained from other sources. The only advanced tool used for the assessment is ESRSI's computer software, ArcGIS, which requires a license and some software-specific expertise. The complete list of data used for the assessment includes a geological map of Karnataka (Mundkur, 2010), the wave, tide and storm maps included in the original CHW framework paper and published by Masselink and Hughes (2003), supplementary information on local tidal range (Nayak and Hanamgond, 2010), the UNEP-WCMC World Atlas of Coral Reefs (Spalding et al., 2001), Google Earth satellite images with timeline and ground elevation functions (Google, 2012), Bing Maps available in ESRI's ArcGIS (ESRI, 2012; Microsoft, 2012) and two sections of Rapideye satellite images covering some low resolution gaps in the Bing maps (GRAS, 2012). The following sections describe how each of the coastal classification circles of the CHW has been determined based on the available data, and a thorough description of the different CHW classification categories can be found in Rosendahl Appelquist (2012).

4.1. Classification circle 1 – geological layout

The geological layout is determined based on an ordinary geological map and Google Earth's satellite images and ground elevation function. The geological layout type is found by combining information from these three data sources and a new evaluation is made every time any of the parameters i.e. geological base material, geomorphology and coastal slope changes significantly.

For Karnataka, the determination of geological base material is relatively straightforward as the coastline is mainly composed of laterites. However, as the assessment is carried out remotely, it is not possible to assess the compaction and cementation level of the laterites in the field. In the practical classification, sloping laterite coastlines have been grouped into the sloping soft rock coast category, while flat laterites have been grouped into one of the flat coastal categories. In cases where the sloping laterites are heavily cemented, this may lead to an overestimation of the hazard levels as the coast would otherwise fall into the sloping hard rock coast category. Additional field verification of the laterite cementation would therefore be appropriate for implementing Step 2 and 3. Another challenge to the categorisation of geological layout is that smaller hard rock headlands are not visible on the geological map of Karnataka although they are visible on Google Earth's satellite images. In most cases, however, it is sufficient to rely on Google Earth as these structures are relative easily identified.

The slope of the coastline is determined using Google Earth's ruler and ground elevation functions. The elevation function is based on a digital elevation model from NASA's Shuttle Radar Topography Mission and its altitude resolution varies by country. Large parts of USA currently have a resolution of 10 m but most other world regions including India have a lower resolution (Wikipedia, 2012). When the ground elevation is assessed, the smoothing of the contours by the elevation model can be easily noticed, which may lead to some errors in flat areas adjacent to elevated regions. However, as the coastal classification system only requires input on whether the coast is sloping more or less than 3–4%, 200 m inland of the MSL, the error is not expected to significantly affect the classification accuracy. Large sections of Karnataka's coastline are sloping to some degree and it is therefore necessary to be cautious when conducting the elevation assessment. The fact that several of the barriers along Karnataka's coastline have a slope of more than 3–4% also increases the need for a careful slope assessment.

The coastal morphology is determined based on a visual assessment of Google Earth's satellite images. Form elements presented as barriers, deltas, tidal inlets, sand spits and river mouths can be easily identified with a zoom level of 5–10 km. The remaining mainland coastline can be categorized based on geology and slope.

4.2. Classification circle 2 – the wave exposure

The wave climate is determined based on the wave maps in the original CHW paper (Rosendahl Appelquist, 2012; Masselink and Hughes, 2003). Since Karnataka is located outside the areas with swell/monsoon wave climates, the level of wave exposure is dependent on the free fetch and wind speed. It was not possible to obtain detailed wind data for the region and it was therefore decided to rely solely on the free fetch to determine the exposure levels for this classification. As the wind is blowing from the open ocean during the SW monsoon season, the free fetch is likely to be an appropriate proxy for the possible wave heights. The assessment has used Google Earth to determine whether the free fetch for a given coastal stretch is less than 10 km, 10–100 km or above 100 km which are the defined boundaries for protected, moderately exposed and exposed coastlines in the CHW framework. Generally, the outer reaches of Karnataka's coastline are directly exposed to the waves of the Arabian Sea and categorized as exposed while the coastlines of the inner estuaries are classified as protected. As the coastline varies between estuaries and open coast, the moderately exposed category has generally not been applied.

4.3. Classification circle 3 – the tidal range

The tidal range is determined based on the tidal range maps included in the original CHW paper (Rosendahl Appelquist, 2012; Masselink and Hughes, 2003). However, as Karnataka is located close to the border between the micro- and meso-tidal types, supplementary data has been collected on the local tidal range. This data indicate that all of Karnataka generally stays within the micro-tidal category with tidal range increasing towards the northern part of the state (Nayak and Hanamgond, 2010). It was therefore decided to apply this category for the coastal classification. Meso-tidal conditions may be present inside some of the estuaries due to the local coastal configuration but because of the limited data availability it is difficult to verify. However, the tidal range in these locations is still expected to stay close to the border between micro- and meso-tide. The micro-tide category is therefore applied consistently to the full coastline of Karnataka.

4.4. Classification circle 4 – the flora/fauna

The flora/fauna is determined based on a visual assessment of the coastline in Google Earth combined with information on its geographical location and global coral reef data. As Karnataka is situated in the tropical climate zone, flat protected coastlines such as coastal plains and barriers generally have some kind of mangrove vegetation in protected locations, but due to the relatively low tidal range, the mangrove areas are of intermittent character. Coral reefs are generally non-existent along Karnataka's coastline and it is uncertain whether past sporadic coral habitats still exist (Spalding et al., 2001). Therefore, the coral reef option has not been applied to any parts of the coastline.

4.5. Classification circle 5 – the sediment balance

The sediment balance evaluation uses remote sensing information from Google Earth's satellite images and timeline function to compare images of the coastline taken over the last decade. Generally, coastal stretches have been assumed to have a sediment balance/deficit unless it is very clear that they have a sediment surplus in order to avoid underestimating some of the hazard levels. For the exposed, littoral coastlines of Karnataka, it has to some degree been possible to get a reliable indication of the sediment balance using Google Earth's images from the last 5–10 years, as the changes in the vegetation line in most cases is clearly visible. For protected coastlines, however, it has been difficult to visually assess smaller temporal changes based on the satellite images and these coasts have therefore in many cases been placed in the balance/deficit category. In addition to the general challenge of estimating the sediment balance, Google Earth has some gaps in its timeline function meaning that some areas are only coved by one satellite image, making temporal assessments impossible. This is the case for the coastline at Kodi Bengare to Kemmannu; Kota; Marvanthe; and Ternamakki to Kasarkod and these coastlines have therefore been placed in the balance/deficit category. Sometimes only two images with a few years in between are available in Google Earth which also leads to uncertainty in the evaluations.

4.6. Classification circle 6 – the storm climate

The storm climate is determined based on the wave/storm maps included in the original CHW paper (Rosendahl Appelquist, 2012; Masselink and Hughes, 2003). As Karnataka is indicated to be under tropical storm influence, the complete coastline is classified to be located in a tropical cyclone area.

5. The GIS procedure

The coastal classification and hazard assessment procedure is carried out in ArcGIS based on a Hybrid Bing Map. As the resolution of the satellite images is generally better in Google Earth than in Bing Maps, is was considered to conduct the whole classification in Google Earth. However, due to the technical limitations of Google Earth, it was decided to conduct the classification in ArcGIS, using Google Earth as data source.

As a first stage a geodatabase is created in ArcGIS that will contain all coastal classification data as well as data on hazard levels. In order to have a relatively detailed and up-to-date digitized coastline of Karnataka which can be used for the coastal classification, a new line feature class is created in the geodatabase referencing the WGS1984 Web Mercator Auxiliary Sphere coordinate system. It should be noted that other coordinate systems may be more appropriate for other world locations. The line feature is then used for creating a digitized coastline of Karnataka by manually digitizing the coast at the approximate Mean Sea Level (MSL) with a zoom level of 2–4 km in the ArcGIS window. Because the satellite images are taken at different times during the tidal cycle, the line feature will most likely deviate from the actual MSL but this is considered of minor importance for the purpose of this assessment, as it only requires a relatively accurate and up-to-date coastline. The digitizing is carried out with an accuracy of about 5–10 m leaving gaps for river mouths and tidal inlets. Islands are digitized as separate units. This line feature then constitutes the foundation for the further coastal classification and the hazard maps.

To facilitate the assessment of the coastal slope and sediment balance, two supplementary line features are created in Google Earth. The line feature for facilitating the slope evaluation consists of a range of shore-parallel line sections that are drawn landwards of the coastline in all coastal areas with a slope greater than 3–4%. This enables the user to quickly determine whether a particular coastal area is sloping or not when carrying out the coastal classification. The slope of a particular coastal section is determined by manually placing the cursor over the first 200 m landwards of the coastline in Google Earth, taking note of elevation levels given in the button of the Google Earth window. This procedure is carried out for every approximately 100–200 m of coastline at a Google Earth zoom level of 2–4 km. The line feature for facilitating the sediment balance evaluation consists of a continuous line drawn on the approximate coastal vegetation line. When the coastal classification is carried out, the sediment balance can be assessed by comparing the satellite images taken at different times through Google Earth's timeline function, looking at how the coast has been developing compared to the digitized, most recent coastline. Since the satellite images are taken at different tide levels and time of the year, the beach width cannot be reliably used for determining the sediment balance, but the vegetation line is considered as a relatively good indicator for the general sediment balance.

The coastal classification based on the CHW is carried out on top of the digitized coastline by using a polygon feature created in the geodatabase with the same coordinate system as the line feature for the coastline. The polygons are used to split the original line feature into sections, each representing a different coastal environment defined in the CHW framework. The classification is done by manually drawing a separate polygon for each coastal classification category along the coastline, based on an evaluation of the classification parameters mentioned in the data section earlier. When drawing the polygons, it is important to enable a snapping environment to ensure that the polygons are snapped properly to each other. The name of the coastal environment in question is then typed into the attribute table for each polygon in the ID field. As the

ID field in the attribute table only accepts numbers, the coastal environments in the CHW framework are assigned values between 1 and 113, with 1 given to the CHW type CP-1. Because the classification of each coastal stretch is carried out based on the CHW and the listed input data, the user has to decide on an appropriate coastal type and its extension before each polygon is completed. Sometimes a coastline can maintain the same properties for longer distances, meaning that the length of a polygon can range from less than fifty meters to several kilometres.

The polygons are subsequently used to divide the initial digitized coastline into sections, each representing a specific coastal category. The hazard levels given in the CHW and further described in the original CHW paper (Rosendahl Appelquist, 2012) are then typed into a separate attribute table that is joined to the attribute table of the coastal classification file. Based on this, five different hazard maps are created for the respective hazards types and the different hazard levels are assigned a colour code. Finally, a background land polygon and a text layer with city names are created to improve the readability of the hazard maps and the relevant hazard statistics is extracted from the GIS.

6. Results

The results from the application of the CHW framework on the coastline of Karnataka are an overview table of the most common coastal types in Karnataka, an overview table of the prevalence of the different coastal hazards and a range of sub-regional and regional hazard maps. Table 1 shows the top 10 most common costal types in Karnataka in distance as well as in percentage of the total coastline. In this assessment, the total length of Karnataka's coastline has been calculated to 647 km which is significant more than many estimates given in the literature. This is the case as the coastline in the assessment includes the open ocean coastline as well as back-barriers, estuaries and islands. From the table, it can be seen that the 10 most common coastal types make up over 90 percent of Karnataka's coastline. The most common types are the sloping soft rock coasts, SR-5 and SR-17, followed by the sloping hard rock coast HR-1. Special coastal elements such as tidal inlets, sand spits and river mouths are also relatively common, making up 13 percent of the total coastline. The flat coastal environments, coastal plain CP-13, delta DE-13 and barrier BA-13 are also quite widespread making up 9 percent, 8 percent and 3 percent respectively.

The hazard profile of the coastline of Karnataka is shown in Table 2. The table shows the distribution of the different hazards and hazard levels as a percentage of the total coastline length. From the table it can be seen that erosion constitutes the most prevalent hazard type as 61 percent of Karnataka's coastline has a high or very high inherent hazard for erosion. The hazards of flooding and salt water intrusion are also relatively widespread as 39 percent of the coastline has a high or very high inherent hazard for both of these hazard types. 32 percent of the coastline has a high or very high inherent hazard of gradual inundation while 19 percent has a high or very high inherent hazard of ecosystem disruption.

Fig. 2 shows the hazards of erosion and flooding for northern Karnataka and is an example of how the CHW framework can be used for sub-regional hazard mapping. The hazard class 1 is low inherent hazard, 2 is moderate inherent hazard, 3 is high inherent hazard and 4 is very high inherent hazard. The maps give a relatively good overview of areas that requires special attention and can provide a basis for sub-regional planning and management decisions.

Fig. 3 shows a range of overview hazard maps for the state of Karnataka and includes the hazards of ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding. The hazard classes are the same as for Fig. 2. Generally, the maps are not as applicable for planning and management purposes as the ones shown in Fig. 2 but gives a general overview of the hazard presence along the coastline of Karnataka and can be used for identifying hazard hotspots. For the inherent hazard of ecosystem disruption, it can be seen that the outer coastline of Karnataka generally has a low or moderate hazard level, while the very high hazard levels are found in relation to the estuaries. The same pattern can be seen for gradual inundation and salt water intrusion, while large sections of Karnataka's outer coastline have a high or very high hazard level for erosion. The high and very high flooding hazards can especially be found in association with the estuaries and some of the exposed coastal plains.

7. Uncertainties and limitations

The hazard assessment is carried out at sub-regional and regional scale, meaning that the hazard maps are not intended to guide local development activities but rather to assist regional planners and decision-makers in getting an overview of the hazard profile of the coastline and in indentifying hazard hotspots. Whereas the maps covering the whole Karnataka are good for providing an overall picture, the more detailed maps are more appropriate for sub-regional planning purposes. Since the assessment is based on published geophysical data and remote sensing information, several uncertainties exist that should be addressed by field verification if a more detailed assessment is needed. However, as a Step 1 assessment, it is considered to provide a reasonably reliable overview of the hazard presence and the location of hazard hotspots.

An important uncertainty that could be addressed by field verification relates to the geological layout and especially the compaction and cementation level of the coastal sediment. The coastal stretches composed of laterites could be compacted and cemented to various degrees and a particular coastal stretch could therefore fall into the sloping soft rock or sloping hard rock categories depending in their cementation level. This could change for different sections of the coastline and a random field assessment of the compaction/cementation levels of the sloping laterite

Table 1
The top 10 most common coastal types in Karnataka.

Coastal type	Length (km)	Percent of coastline
Sloping soft rock 5 (SR-5)	146	23
Sloping soft rock 17 (SR-17)	118	18
Hard rock 1 (HR-1)	100	16
Tidal inlet/Sand spit/River mouth (TSR)	84	13
Coastal plain 13 (CP-13)	58	9
Delta 13 (DE-13)	49	8
Barrier 13 (BA-13)	16	3
Coastal plain 1 (CP-1)	14	2
Delta 15 (DE-15)	13	2
Barrier 1 (BA-1)	12	2
	609	94

Table 2
The distribution of hazard levels in percent for Karnataka's coastline.

Hazards/Hazard level	Low	Moderate	High	Very high
Ecosystem disruption	24	56	0	19
Gradual inundation	61	6	13	19
Salt water intrusion	61	0	25	14
Erosion	16	24	21	40
Flooding	61	0	0	39

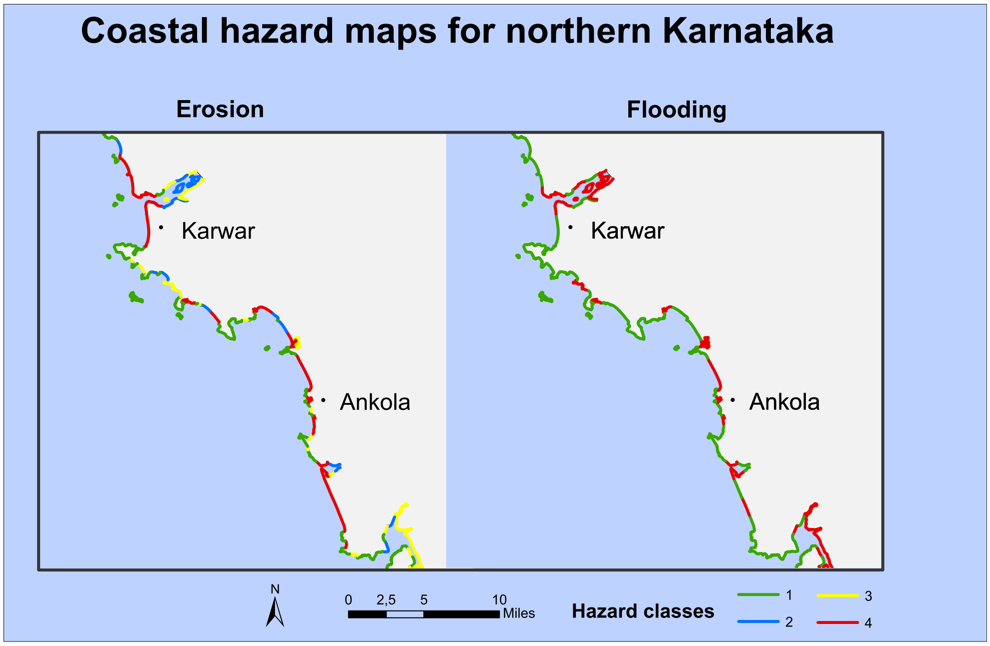

Fig. 2. Coastal hazard maps for northern Karnataka.

coastlines could therefore provide an indication of the prevalence of the different conditions. The assumption that all sloping laterite coastlines fall into the sloping soft rock category is considered reasonable as most laterites becomes relativity soft if they are made wet. However, this may overestimate the hazard levels at locations where the laterites are heavily cemented. The relatively low resolution of the geological map of Karnataka also means that it is necessary to rely on the satellite images to identify smaller sloping hard rock features such as headlands. Additional field assessments could have been useful for verifying this, although the resolution of the Google Earth images is generally sufficient to identify these structures with a relatively high accuracy.

The flora/fauna category is also associated with some classification uncertainty that could be addressed with field verification as it is almost impossible to evaluate the percentage of vegetation cover on sloping soft rock coastlines based on the satellite images available in Google Earth and Bing Maps. Because of Karnataka's favourable climatic conditions for full year vegetation growth, it is assumed that all sloping soft rock coasts are vegetated unless clear counter-indications are present. As this parameter only has a minor

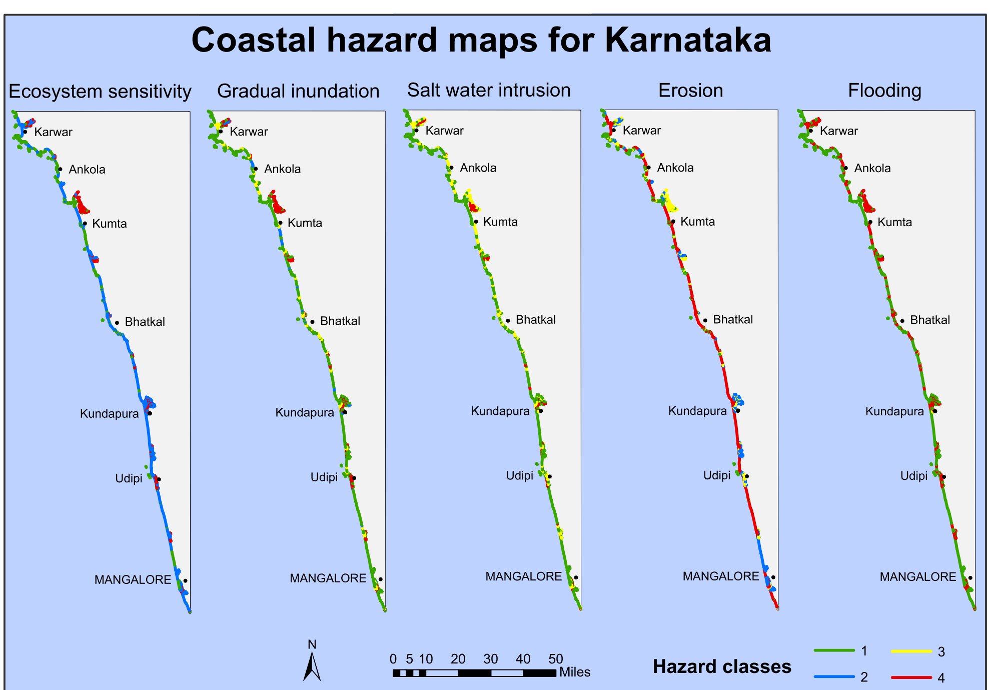

Fig. 3. Overview maps of coastal hazards for Karnataka.

effect on the hazard levels of ecosystem disruption and erosion, it is considered to be an acceptable uncertainty at this step in the hazard assessment, but for implementation of Step 2 or 3 additional investigations would be needed.

The satellite images used for the assessment constitute another source of possible uncertainty. In areas where the resolution of Google Earth and Bing Maps images are so low that it complicates detailed assessment of the coastline, some uncertainties are related to the coastline configuration. More problematic, however, is the fact that some locations are only coved by a single satellite image in Google Earth's timeline function or only have two images with a few years in between. In the first case, temporal assessment of the sediment balance is impossible while in the second, it is associated with significant uncertainties. This problem may be addressed for most world locations in the coming years as Google Earth continuously adds new satellite images, but for this test-assessment it constitutes a significant source of error. Furthermore, the sediment balance of protected coastal stretches is difficult to assess visually with the current resolution of the satellite images, but this may also improve in the coming years. To avoid underestimating the hazard levels, this assessment generally assumes that a coastal stretch has a sediment balance/deficit, unless it is very clear that it has a sediment surplus.

Since Google Earth and Bing Maps are comprised of a range of different images taken at different times of the day and year, one also compares images taken during different points in the tidal and sedimentary cycles. With the annual erosion/accumulation cycles of large parts of Karnataka's coastline mentioned earlier and a tidal range close to two meters, this comparison can be problematic. The possible error arising from this is partly addressed in the classification by using the vegetation line as reference when evaluating the temporal coastal developments, but it still adds some noise to the assessment. Ideally, the sediment balance should be based on satellite images captured over several years, at the same time of the year and at the same point in a tidal cycle. The current approach, however, is expected to provide acceptable results given the resolution and purpose of the assessment. If more detailed information is needed for planning purposes, aerial photos, field assessments and interviews could improve the reference data.

The human alteration of Karnataka's coastline constitutes another source of uncertainty. Coastal protection work has been carried out along Karnataka's coastline in the past decades, impacting the natural dynamics. At sub-regional and regional scale, however, these activities are not likely to have a major effect on the hazard profile, as they are relatively locally focused and mainly based on hard engineering approaches. Legal and illegal sand mining from the beaches, however, could have some impact on the sediment balance evaluations, but the effect is unlikely to significantly affect the hazard assessment at this step. However, an implementation of Step 2 or 3 would require further investigation of the scale and geographical focus of these activities. Heavily modified or artificial urban coastlines such as those of the city of Mangalore are likely to be surrounded by some errors in the CHW framework, since the framework only gives information on the natural inherent hazards of the coastline before it was turned into an artificial coast. But apart from this urban coastline, human alteration of Karnataka's coast is not expected to cause significant problems for the assessment at this step.

Some limitations are associated with the design of the CHW framework itself. The CHW defines a special category for tidal inlets/sand spits/river mouths as these generally are very dynamic environments with high hazard levels. However, a few tidal inlets in Karnataka have a headland next to the inlet, meaning that the hazard levels are significantly lower than for the tidal inlets defined in the CHW framework. As the hazard levels of these inlets are more in line with that of the sloping hard rock coast category, this category has been applied to these inlets, although it does not adhere to the CHW principles. Also, some of Karnataka's river mouths are so small that they could rather be considered a stream than a river mouth. The guidance given in the CHW framework to apply the river mouth category to the coastline 1 km on each side of the river mouth is therefore regarded as inappropriate. In this assessment, the river mouth category is therefore only extended 0.5 km on each side of the river if it is of stream-size.

The process of carrying out the practical classification process and drawing the polygons is also surrounded by some uncertainty as it based on a manual evaluation of the coastal data. Since the evaluation procedure for the different classification parameters are well defined in the original CHW paper (Rosendahl Appelquist, 2012) and in this paper, the assessment method is not expected to lead to significant greater uncertainty than an automated assessment, as that would still be based on some predefined evaluation procedures. However, the manual approach means that two parallel studies of the same area would be likely to come up with slightly different assessment results. As the CHW framework is designed as a screening tool that can be applied in developing countries and data-poor locations, it tries to strike a balance between simplicity, low-tech design, data requirements and accuracy. The magnitude of the uncertainty related to this manual procedure is therefore regarded as acceptable given the detail and purpose of the assessment, but it is important to keep this uncertainty and possible source of error in mind when using the CHW framework for practical assessments.

8. Regional planning and management perspectives

The assessment process outlined in the previous sections is intended to showcase a procedure for applying the CHW framework for regional multi-hazard-assessments. The hazard maps developed for Karnataka can be used for identifying hazard hotspots, getting an overview of the hazard profile of the coastline and detecting areas where human activities may be at risk from future coastal dynamics. As broader coastal hazard assessments are generally non-existent for most developing countries, the methodology provides a possibility for planners and managers to increase their knowledge base in areas with limited data availability. Likewise, it offers a simple system for initial hazard screening in areas where data is readily available.

The hazards covered in the assessment framework are of very different character and hence have very different consequences for human activities. Ecosystem disruption, gradual inundation, salt water intrusion and to some degree erosion is likely to occur gradually and worsen with climate change. Flooding, on the other hand, is an abrupt and potentially disastrous event that will become more likely with rising sea level and increasing precipitation intensity and storm activity. The different hazards are to some degree related to each other, but only a few coastlines have high inherent hazard levels for all hazard types. Coastal planners and managers therefore need to address the specific hazard combination for each coastal stretch in question.

For the state of Karnataka, all hazard types are present but apply to different stretches of the coastline. The hazard of ecosystem disruption is especially related to the mangrove areas in the extensive protected estuary and back-barrier coasts and in the short term, it will probably not be possible to distinguish the climate change hazards to these ecosystems from the major current drivers of change such as overfishing and clearing of mangroves e.g. for aquaculture. In the longer term, however, climate change is likely to pose an additional risk to these systems due to especially sea level rise. Enhancing their resilience at this point should therefore be a priority and is likely to be economically viable as these environments provide valuable services such as flood protection and breeding ground for marine fisheries (Millennium Ecosystem Assessment, 2005).

The hazard of gradual inundation is mainly related to the low-lying protected estuary coasts and the coastal barriers of Karnataka. Barriers with a sediment deficit are already at significant risk and people in these areas may face losing their land permanently to the sea if no countermeasures are taken. Simple dikes could protect the areas to some degree, but on a longer term, a managed retreat or extensive dike systems may be necessary. If dikes are constructed, however, they should always be of a decent quality to avoid giving people a false sense of security of flood protection.

Salt water intrusion is especially a hazard to Karnataka's coastal plans and barriers. The magnitude of this hazard may increase due to human extraction of groundwater and hence it is essential to monitor the groundwater reservoirs and water extraction to avoid that salt water is replacing the current freshwater resources. Simple water balance calculations can be carried out for the barriers to see if the current water extraction practices are sustainable, but gradual inundation and flooding events can completely eliminate the groundwater reservoirs in these locations. In that case, other long-term options for freshwater supply should be investigated and a managed retreat from some of the barriers may be considered.

Erosion is a major general hazard to Karnataka's coastline and many areas are already suffering from the effects of this. Although the state only has limited experience with beach nourishment, possible nourishment schemes combined with groins or breakwaters may be a viable hazard mitigation option for densely populated sections of the coastline. The challenge in this regard is likely to be offshore sand availability, as large quantities of sediment may be needed. Since the cost of sand can vary tenfold depending on dredging conditions and sediment transport distance, it can be a costly management option if sediment is not readily available. A purely hard-engineering strategy may be less costly, but will destroy the natural dynamics of the coastline and the associated natural services, and for coastal stretches used for recreational activities this may not be a viable option. A managed retreat may be relevant for areas experiencing extensive erosion, but with a densely populated coastline, some kind of hold-the line strategy is likely to be necessary in most locations.

Flooding constitutes a serious hazard for the low estuary islands, barriers and coastal plains of Karnataka, and should be addressed properly due to its potential disastrous consequences. Flood warning systems and flood shelters could provide economically viable solutions in the short term, but as repeated floods can disrupt agricultural production, freshwater supply and infrastructure, some kind of dike system may be necessary as a long term solution. As most hazard mitigation options have effects on other hazards than the ones they are primarily designed to address, it is important to consider the possible effect of a given management option on all hazard types. Dikes and hard engineering measures are good at mitigating hazards of flooding and erosion, but often increase the hazards of ecosystem disruption as they disrupt the natural coastal dynamics. For each section of the coastline, it is therefore necessary to consider which hazards are the most important to mitigate and what consequences different mitigation strategies have on all hazards. Because flooding can have dramatic consequences on human activities and be potentially life threatening, mitigating this hazard may in many cases be given higher priority than other hazards such as ecosystem disruption. Hence coastal planner should not only look at which hazards are scoring highest in the CHW framework but also consider which hazards are most problematic to the human activities taking place in a particular coastal area.

A key parameter for deciding on appropriate mitigation strategies is therefore the human activities taking place in a coastal area. Measures of this could be population density, presence of important infrastructure, cultural heritage and various economic activities. As many countries have GIS data on economic activities and global population density data is publicly available (SEDAC, 2013) this information can be added to the GIS used for the coastal hazard assessment to identify areas with specific combinations of coastal hazards and human activities. In this way, the CHW framework can be used to identify areas with e.g. high flooding hazards and high population density. Combing the hazard maps with socioeconomic data could thereby provide a good base for supporting coastal management decisions.

9. Conclusion

The CHW framework has been very suitable for carrying out sub-regional and regional hazard assessments at the scale of the state of Karnataka. It has been possible to conduct the hazard assessment based on easily obtainable data and the assessment procedure outlined in this paper should be replicable in most other areas of the world yielding results of similar quality. The assessment is associated with some uncertainties as it relies solely on published geophysical data and interpretations of remote sensing information, but the uncertainties are considered acceptable given the resolution and goal of the assessment. For more detailed hazard assessments at Step 2 and 3, additional field verification is recommended to improve the assessment accuracy and reliability seen from a decision support perspective. Attempts have been made to keep the assessment procedure relatively simple, with a manual application of the coastal classification in the GIS. This makes the coastal classification process relatively straightforward but at the same time increases the possibility for human misjudgements due to the subjectivity of the procedure. Users should therefore be aware of these risks when using the CHW framework and the assessment procedure outlined in this paper. Supplementing the physical CHW assessment with socioeconomic data may in many cases be relevant for improving the information base for coastal planners and managers. This would provide CHW users with a combined picture of physical hazards and societal activities which could be relevant for supporting long-term planning decisions.

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